THE MASS CUSTOMIZATION OF SANDAL OUTSOLES FOR FEMALE SIZE OUTLIERS UTILIZING PARAMETRIC MODELING AND 3D PRINTING

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The Mass Customization of Sandal Outsoles for Female Size Outliers Utilizing Parametric Modeling and 3D Printing

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LIST OF SYMBOLS AND ABBREVIATIONS

3D	Three Dimensional
CAD	Computer Aided Design
CNC	Computer Numerical Control
DFAM	Design for Additive Manufacturing
FDM	Fused Deposition Modeling
FL	Foot Length
FW	Foot Width
IOT	Internet of Things
ISO	The International Organization for Standardization
IT	Information Technology
mm	Millimeter
USD	United States Dollar

SUMMARY

For many women, finding proper fitting footwear is difficult and customized footwear has been out of reach for most due to high costs and lack of access. Standard shoe sizing has historically been based off of an average male foot size, resulting in a poor fit when scaled or graded to create women's sizes. This problem is especially prevalent in casual and athletic footwear where a men's last is used to produce women's footwear. This problem is compounded for women who fall far to either side of the bell curve, 10^{th} and 90^{th} percentile, where shoes in their sizes are less common. The rise in mass customization through technologies such as 3D printing has the possibility to change this. This study aims to determine if a customized sandal outsole can be produced by a parametric CAD model and 3D printed for females whose foot lengths fall into the <10% and >90%, according to global CAESAR (Civilian American and European Surface Anthropometry Resource) data. This project proposes a parametric sandal outsole model that will accommodate sizing outliers at both ends of traditional women's shoe sizes. Subjects measured their foot width and foot length and the results were used as inputs into the parametric outsole model. The resulting model was 3D printed and test fitted on the subjects who rated the fit. Results indicated an acceptable fit of the prototype footwear.

CHAPTER 1. INTRODUCTION

For many women, finding proper fitting footwear is difficult. For women with much larger or smaller feet than average, finding properly fitting footwear is a great challenge. Since the introduction of women's sizes in the United States in 1880, Women's sizes have traditionally been a proportionally scaled down version of shoe lasts developed for men [1, 2]. This practice of using the same or a proportionally scaled down men's last for both men's and women's shoes is still continued today and can be seen mostly in casual and athletic running shoes [3]. It has been widely reported that women's feet differ significantly from men's in a multitude of distinct foot measurements [2, 4]. Around the world, women's feet are narrower than men's feet but other measurements vary depending on the geographical region [4]. Because of the different morphology of men's and women's feet, it is not recommended to share lasts across sexes [3].

For women with outlier sizes, <10 percentile, Nike size 5.5, and >90 percentile, Nike size 9.5, the problem of finding footwear is compounded by the distribution of footwear and the sizes that footwear manufacturers choose to make. The average women's size is closest to Nike size 7.5. Nike uses a women's size 7 as its women's sample size and men's size 9 for men's shoes. [5] Sample size shoe is the masterpiece that all other shoes of a particular model are scaled or graded off of to make other sizes. Table 1 shows how sizes are distributed across the 3 most available types of shoes on Zappos.com, a reputable online shoe seller. It is clear that not all companies manufacture half sizes based on the drop off in shoe count at half sizes. Shoe counts also drop off dramatically at size 5.5 or about the 10th percentile. It does appear that more shoes are offered at the larger sizes but drop off as sizes go up, especially at half sizes. It is also important to note that not all shoe manufacturers' sizes are the same size. One company's size 7 can be different than another company's size 7. See the below for comparison of measurement charts, Table 1. These distributions of shoes and sizes force women to settle for a "good enough" fit or compensate by purchasing men's sizes or kid's sizes.

Table 1 – Zappos Women's Shoe Size Distributions. *Total number of sandals, heels, and athletic shoes observed at each size.

Global Percentile (CAESAR)	Z Score	Size in mm (Nike)	U.S. Womens Size	Zappos.com Womens Shoes Available*	% decrease from max. quantity of shoes.
1.25%	-2.24	212	4	1,231	-95.36%
2.74%	-1.92	216	4.5	1062	-95.999%
7.49%	-1.44	222	5	15,305	-42.345%
10.03%	-1.28	224	5.5	14,628	-44.895%
18.94%	-0.88	229	6	26,042	-1.8985%
28.77%	-0.56	233	6.5	20,740	-21.871%
40.52%	-0.24	237	7	26,028	-1.9512%
53.19%	0.08	241	7.5	21,900	-17.501%
65.54%	0.4	245	8	26,546	0%
78.81%	0.8	250	8.5	22,137	-16.608%
86.86%	1.12	254	9	26,258	-1.0849%
92.51%	1.44	258	9.5	20,721	-21.943%
96.08%	1.76	262	10	25,841	-2.6557%
98.46%	2.16	267	10.5	8,482	-68.047%
99.34%	2.48	271	11	19,264	-27.431%
99.74%	2.8	275	11.5	2,929	-88.966%
99.91%	3.12	279	12	6,513	-75.465%

Table 2 – Women's shoe sizes across manufacturers. Manufacturers' sizes in mm.

U.S. Women's Sizes	4	4.5	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10	10.5	11	11.5	12
Nike	212	216	222	224	229	233	237	241	245	250	254	258	262	267	271	275	279
Adidas			221	225	229	233	238	242	246	250	255	259	263	267	271	276	280
Teva			220	225	230	235	240	245	250	255	260	262	265	270	275	280	285
New Balance	210	215	220	225	230	235	240	245	250	255	260	265	270	275	280	285	290
Zappos Chart	208	213	216	222	225	230	235	238	241	246	251	254	259	262	267	271	276

There have been many attempts to create a better fitting shoe but solutions are hindered by manufacturing, inventory, and other operation logistics. One manufacturer introduced ¼ sizes in an attempt to give people more sizing options but this venture failed due to the large inventory needed [1]. The Mass Customization of footwear for improved fit is currently centered around foot measurements and matching a foot to a closely matching last or shoe model. Mass Customization is defined as company's ability to quickly adapt their resources to produce a product that is customized for a customer at a cost comparable to mass production [6]. Custom 3D printed insoles are also used to further customize shoes. There have been several attempts at completely custom 3D printed footwear and even custom 3D printed sandals made by OESH. No footwear manufacturer was found that explicitly sought to understand outlier sizing, mass customization, or explained their models as parametric.

The mass production of footwear must adapt to new manufacturing paradigms that offer users mass customization of footwear through additive manufacturing. This thesis explores the development of a sandal designed to custom fit females whose feet are considered outliers along the bell curve of average female foot sizes, less than the 10th

percentile and greater than the 90th percentile, using a parametric model. An individual's foot length and width are the driving inputs for the parametric model.

1.1 Specific Aims of the Study

This project aims to design a parametric sandal outsole model for female size outliers, <10th percentile or >90th percentile, that can be manipulated based on foot dimensions and produced using additive manufacturing. In theory, a parametric CAD model, designed in a way to be manipulated with relative ease and limited inputs, can be manipulated using measurements from an end user to produce a footwear sole model ready for manufacturing. The CAD model personalized using the measurements from the end user can then be made using additive manufacturing methods such as 3D printing. In this study the resulting physical model would then be sent to the end user and accessed whether it provides an acceptable fit.

The specific steps to achieve the project's aims are listed below.

1. Evaluate footwear related data from a questionnaire.
2. Collect foot size data from individuals in a way that could be conducted at home.
3. Design a sandal outsole in a parametric CAD software that can be easily manipulated with a subject's foot dimensions.
4. Insert subject's foot length and width measurements into the parametric CAD model.
5. Produce the model using additive manufacturing.
6. Evaluation of the sandal on a subject's foot for fit.
7. Use evaluations to make recommendations for path forward and reach conclusion

1.2 Significance of the Study

The results of this study will impact the way footwear is designed for mass customization and custom fit. The purpose of this thesis is to reimagine modern footwear sizing. With new technologies in manufacturing, standardization of sizing is no longer as important. The constraints of manufacturing fixtures, molds, and dies are no longer viable. A person no longer needs to fit into a predetermined shoe size. This study focuses on females with a foot length or width that falls outside of these parameters. For the purposes of this thesis outlier females are defined as being in the <10% or >90% in foot length based on data collected by CAESAR (Civilian American and European Surface Anthropometry Resource) [7]. Table 3 shows the data from the CAESAR resource used in this thesis.

Table 3 – CAESAR Female Foot Measurements

Category	Sample Size	Average	Median	Standard Deviation	Skewness	Kurtosis
foot_brth_lt	2260	93.9	93.9	7.39	-0.0356	0.313
foot_brth_rt	2265	94	94	7.11	-0.0838	0.57
foot_length	2344	240	240	12.5	0.167	0.419

CHAPTER 2. LITERATURE REVIEW

2.1 Sizing

Shoes were once made specifically for an individual. Either by the individual themselves or by a specialized crafts person. As shoes began being made at scale prior to the Industrial Revolution a sizing system was developed to communicate shoe sizes in certain areas. During the industrial revolution the system for defining the size of the shoes was further expanded upon as the quantities of shoes being produced for consumers skyrocketed.

Shoe sizing has long been a guessing game for companies and customers. It is estimated that 60% of people walk around in the wrong size shoe [8]. Primarily, shoe sizing is based on foot length and foot width.

2.1.1 History of shoe sizing

Shoe sizing can be traced back to the inch measurement system developed in Britain and, according to the Encyclopedia Britannica, was defined by King Edward II as "three grains of barley, dry and round, placed end to end lengthwise" [9]. Shoe cobblers adopted this measurement and made shoes sized to one barleycorn or 1/3 inch [10]. The British system was further developed and is sometimes credited to Randle Holmes in the Academy of Armory and Blazon in the year 1688 [1] . Another sizing strategy developed in Europe around the same time was the Paris Point system based on 2/3 of a centimeter measurement [1]. Roughly 200 years later, an American sizing system was developed in 1880 based on the British System but differed by starting length. The British system starts at 4 inches and the American system starts at 3 and $11/12^{th}$ inches [11]. The ½ sizes are equal to $1/6^{th}$ inch.

The American system was also credited with the creation of a smaller scale for women. The women's scale was approximately 1 ½ sizes smaller than the American men's [1]. The American system also introduced widths marked by letters A, B, D, and E. AAAA is the most narrow and EEE is the widest [11]. Even though these systems, American (U.S.), English (U.K., British), and Continental (Paris Point, European), have little to any base in science they are the most popular sizing conventions in the world. These systems even vary from manufacturer to manufacturer. Table 4 compares how the sizing systems differ by increment and starting unit.

Table 4 – Various Dimensions Used for Different Sizing Systems [1, 11]

Sizing System	Length Increment	Width Increment
English (U.K., British)	1/3 in. = 8.46 mm	1/4 in. = 6.35 mm
American	1/3 in. = 8.46 mm	1/4 in. = 6.35 mm
Continental (Paris Point, European)	2/3 cm = 6.66 mm	5 mm
Chinese	5 mm	3.5 mm
Mondopoint	5-10 mm	5 mm

2.1.2 Mondopoint

The Mondopoint system was developed by ISO (the International Organization for Standardization) in an effort to create a global system for measuring and communicating footwear sizes. The sizing takes into consideration length and linear width of the foot. The Mondopoint system uses Millimeters (mm) as its unit of measurement. According to ISO 9407 Foot length is, "the maximum horizontal distance from the center of the back of the heel (maximum point of heel curve) to the end of the most prominent toe" [12]. This measurement is taken while the subject is standing. The standard defines the linear width of the foot as, "the maximum horizontal distance between the outside swell of the head of the first metatarsal and outside swell of the head of the fifth metatarsal of the foot measured under the same conditions as foot length" [12]. This system has not been adopted globally but is used broadly in Asia. The Chinese (CN), Japanese (JP), and Korean sizing system use this system of measurement. Depending on the manufacturer sometimes units are described in cm instead of mm or only foot length will be used to describe the shoe size.

2.1.3 Sample sizes

Shoes are typically developed in sample sizes before being scaled to other sizes for production. In the United States, the sample size is men's size 9D or women's size 7D [10]. These sizes are used because it is posited that they represent the average man or woman's foot size in the United States. New evidence suggests, that this may not be the best approach, "The National Shoe Retailers Association announced in late 2012 that the most popular shoe sizes have increased over the last 30 years, from size 7½ to 8½ for women, and from size 9½ to 10½ for men" [13]. Sample sizing is another example of the footwear industry being tied to out of date systems that do not represent their customers. All other sizes are scaled up or down from these sample sizes. This process is called grading. In most footwear a last is required to assemble the shoe and acts as a form that the upper is built around and a platform for the shoe to be assembled.

2.1.4 Lasts

A last can be considered as having two rolls. The last is a representation of the foot and provides ergonomic details to give the shoe a good fit. The last also gives the form to a shoe. For example, a last for men's dress shoes may come to more of a point at the toes than say a men's work boot that may be more rounded at the toes. These two rolls are often in conflict with each other. Most footwear manufactures rely on what has been called an artistic last [10]. This is not realistic or functional to walk in but provides a desirable look to the consumer. Examples of shoe lasts can be seen below in Figure 1.

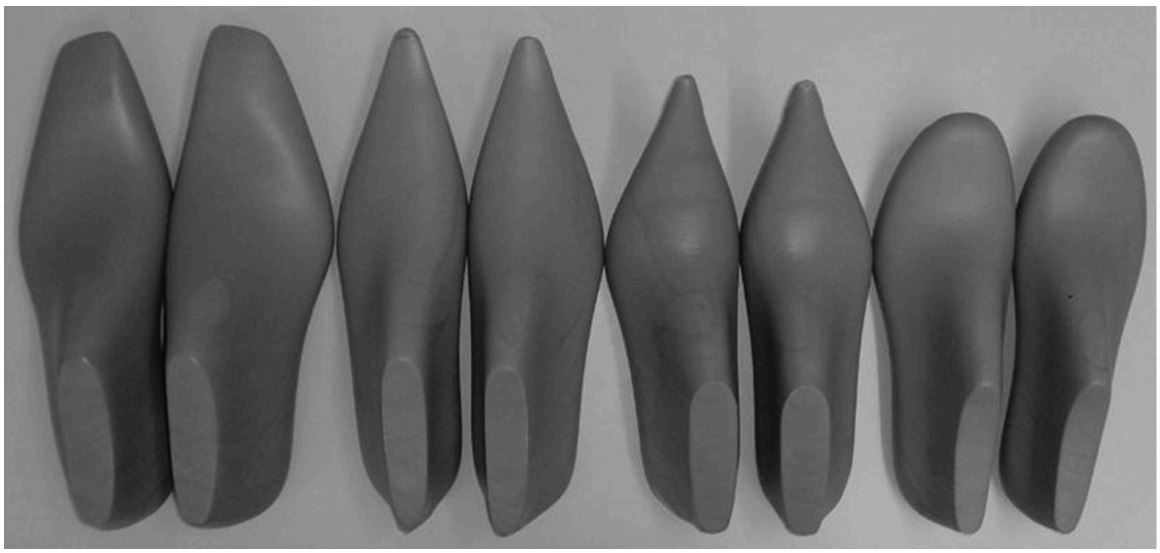

Figure 1 – Examples of Shoe Lasts [11]. The form of the lasts informs the shape of the shoe.

This combination of ergonomic details and aesthetic elements means that certain types of shoes fit people's feet differently. For one person a specific model of shoe may fit perfectly even though the shoe may fit poorly for a person with the same foot size length.

2.1.5 Improving fit through size

To improve fit, companies have offered more size options. In the early 19th century, ¼ length sizes were attempted but failed due to lack of sales [1, 11]. The same issue persists when companies try to stock a large variety of width or outlier lengths of shoes. The investment in molds, stocking, and shipping the shoes make investment in less common sizes unattractive to footwear manufacturers.

This avoidance to offer a wide variety of sizes by footwear manufacturers means people who have less common foot sizes find it difficult to find shoes that fit properly. This is especially true for women with feet size 9.5 and larger and size 5.5 and lower, or those in the 90^{th} and 10^{th} percentiles respectively based on global data from CAESAR.

As mentioned previously, sizing does differ from company to company and within product lines. The two largest footwear manufacturers in the world, Nike and Adidas, differ slightly in their sizing, Table 2. It is important to note that often times manufacturers do not alter last design to include specific morphology to women. Often, men's running shoe lasts are used for women's shoes. This can be traced back to how women's shoes were a derivative of the American Men's system in the late 19^{th} century [1].

2.1.6 Sizing instruments

There have been many ways to measure feet to determine size, but these systems need to be tied to a specific manufacturer due to inconsistences from manufacturer to manufacturer.

Sizing Instruments Listed Below;

Brannock Device

Calipers

2D scan

3D scan

Trace foot then measure

Ruler

Tape measure

2.2 Manufacturing

Currently footwear manufacturers make footwear in predetermined sizes. Factories are set up to mass produce standardized products. Investments are made in standardizing and the use of tooling to make the shoes. According to the authors of “Distributed scheduling to support mass customization in the shoe industry” the modern shoe factory is divided into 5 main departments: cutting, pre-stitching, stitching, lasting, and finishing [14]. A 6th department, molding, should be added to this list because in many shoes the outsole it molded from a rubber, foam, or other material.

The following describes the order of these 6 manufacturing steps. First, the molding department molds the outsole. The molds required for outsoles are milled from a solid metal billet, this fabrication process requires exact and expensive machining [11]. A different mold is needed for every size of shoe being manufactured [15]. Second, in the cutting department, material is cut that will make up the upper of the shoe [14]. For some shoes the cutting department will also cut out pieces that will later be attached to the outsole. The cutting can be done, a number of ways for mass production. The cutting is usually done with a die that is pressed into the fabric to make the cut. For small quantities, the fabric can be cut by hand or with the use of a computer guided cutter such as a laser cutter [15]. Third, the pre-stitching department is where any prework is done to the material that was cut in the cutting department. This work can range from skiving and folding of leather pieces to ensuring fabric pieces are ready to be stitched together [14]. Fourth, the stitching department is where the shoe upper starts to come together. This is a laborintensive process that involves stitching and sowing all the parts together [14]. Many manufacturers use both manually controlled sewing machines and computer guided sewing machines to stitch the fabric together [16]. Fifth, the lasting department is where the upper is stretched over the last to give form to the upper. The last is a mold that represents a foot in the shoe. A different last is used for every shoe size. The last gives the upper structure so the upper can be joined with the sole assembly [14]. The sixth and final step is the finishing department. This is where the shoes are cleaned and placed in their packaging [14]. See Figure 2, below, that illustrates this process flow.

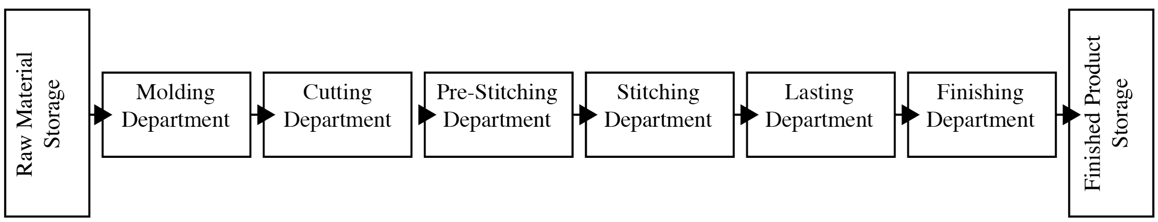

Figure 2 – Manufacturing flow of footwear [14]

2.2.1 Industry 4.0

The manufacturing of shoes in the future will vastly change when more manufacturers begin to adopt mass customization, a company's ability to quickly adapt their resources to produce a product that is customized for a customer at a cost comparable to mass production [6] and will need to rely on new processes and machines to become more agile and viable [14]. This paradigm shift in manufacturing is referred to as Industry 4.0, or the fourth Industrial Revolution. The first Industrial Revolution was when factories began using water and steam to power machinery, the second was the introduction of electricity in the powering of machinery, the third was the application of computers in the automation in factories, and the fourth builds upon the previous Industrial Revolutions by interconnecting machines to share and interpret data and will be primarily IT driven [17, 18]. The primary triggers of Industry 4.0 are described in two sets. First are the social, economic, and political triggers of short development periods, individualization on demand, flexibility, decentralizing, and resource efficiently [18]. The second set is technology and include mechanization/automation, digitalization/networking, and miniaturization [18]. These ideas and technologies combine to form applications of Industry 4.0 in opportunity identification, logistic and supply chain optimization, implementation of autonomous equipment and vehicles, additive manufacturing, and IOT (Internet of Things) [17].

2.2.2 Industry 4.0 and footwear

Footwear manufacturers are particularly interested in Industry 4.0 technologies and have already begun implementing some of the technologies at scale. Adidas has been a front runner of implementing industry 4.0 manufacturing techniques that include additive manufacturing (3D printing) and knitting technologies [19]. Footwear manufacturers are interested in technologies that will enable them to make mass customized footwear tailored to an individual's foot parameters. This is possible by using a blend of technologies introduced by Industry 4.0 such as, additive manufacturing, IOT and 3D scanning technologies. As evident in patents the ability to capture data from a person's foot, interpret that data, and produce a model that can be 3D printed is seen as being highly valuable in the footwear industry [20-22].

2.3 Mass Customization

Mass Customization has been defined as a company's ability to quickly adapt their resources to produce a product that is customized for a customer at a cost comparable to mass production [6]. A challenge for companies looking to adopt mass customization is uncovering the customer specific points that need to be customized to differentiate that product for that individual customer. The points of customization where customers differ has been called 'points of common uniqueness' [6].Within mass customization four categories have been identified as ways to customize: Collaborative, Adaptive, Cosmetic, and Transparent. Collaborative is the process where individual customers participate in a dialogue with the company to influence the design of the product. Adaptive customization allows for the end user to manipulate and alter the product after it has been produced by the manufacturer. Cosmetic customization alters the aesthetic qualities of the product without affecting function. Transparent customization relies on observations of the customer to tailor a product to meet the needs of the customer without direct interaction [14].

Mass customization must consider all sides of a business from marketing, product development, supply chain, manufacturing, and sales.

2.3.1 Configuration

One way in which mass customization can occur is through knowledge-based configuration [23]. The basic architecture of a configuration environment consists of four components, Figure 3 [23]. The user model represents the identified needs of the customer. The configuration knowledge base contains the known limits and component elements. The configuration system is the interface between the customer user model and the configuration knowledge base, taking in these two components and finding connections between the two. The output is configuration, the product that meets the needs of the customers inputs and requirements [23].

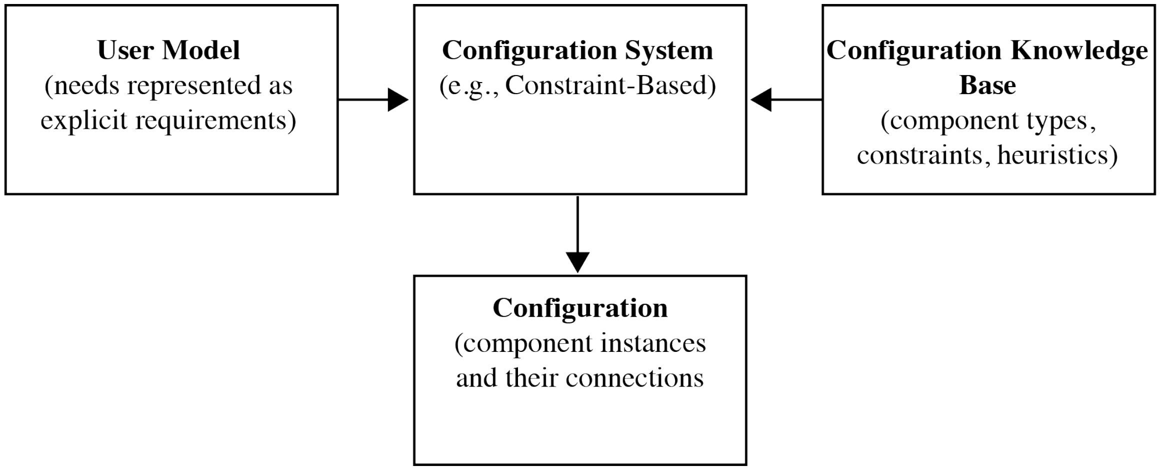

Figure 3 – Architecture of a configuration environment [23].

2.3.2 Mass customization of footwear

A fitting application for mass customization is the footwear industry. A multitude of factors that benefit both manufacturers and customers make this an obvious choice [11, 14].

For customers, the most prominent factor is the inherently individual nature of the human foot. A highly complex structure human feet are made up of 26 bones, 33 joints, connective tissues, muscles, and a network of nerves and blood vessels [11]. All of which are unique to the individual. In addition to people expecting an anatomical fit, i.e. comfort, they also expect the footwear to reflect their own personal style, placing a higher emphasis on fashion and aesthetic. Examples of shoe lasts can be seen above in Figure 1.

Mass customization could also have benefits for manufacturers. The reduction in inventory which carries risk and can lead to a loss of profit in the event of clearance sales or product market ‘flop’. [14]. In other words, mass customization would represent a shift from ‘made-to-stock’ to ‘made-to-order’ [11].

2.3.3 *Elements of mass customization in footwear*

The Science of Footwear identifies and discusses three elements of mass customization of footwear; Style Customization, Comfort Customization, and Function Customization [11]. Style Customization configures the footwear's aesthetic attributes to better reflect the end user's style and personality. Comfort Customization configures the footwear to be more comfortable for the end user. Function Customization configures the footwear for a specific user and/or activity.

2.3.4 *Footwear manufacturers adopting mass customization*

Many footwear manufacturers have adopted mass customization as a technique to differentiate themselves from their competitors and offer a customized product to their customers. The most prominent solution is style customization. This allows a customer to configure the aesthetics of their footwear using an online tool. Manufacturers also offer improved fit by providing a 'best fit' or 'semi- customized' approach. This matches a user's foot measurements with a last from a last library that would provide an acceptable fit to the individual [11, 14]. Nike and Adidas both offer solutions for customers to customize footwear in both Style and Comfort [8, 11].

CHAPTER 3. METHODS

This project aims to design a parametric sandal outsole model for female size outliers, <10th percentile or >90th percentile, that can be manipulated based on foot dimensions and produced using additive manufacturing. In theory, a parametric CAD model, designed in a way to be manipulated with relative ease and limited inputs, can be manipulated using measurements from an end user to produce a footwear sole model ready for manufacturing. The CAD model, personalized using the measurements from the end user, can then be made using additive manufacturing 3D printing. The resulting physical model would then be sent to the end user and should be an acceptable fit. The user research will be conducted in 3 portions. First, a survey is needed to understand subjects' general frustrations with footwear fit and acceptance of custom footwear. At least 30 participants are needed for this section. Second, a participator interview with potential users. In the interactive interview, potential end users will be asked to measure their feet using a variety of methods. The participant will provide the foot measurements to the interviewer. The participant will then evaluate the relative ease of use of each foot measurement method. At least 7 participants are needed for this section. Third, select participants will be given a footwear prototype produced from the measurements they provided. The participant will put the prototype on their foot and evaluate the fit. Fit will be evaluated with photography, visual inspection, and fit questions. At least 2 participants are needed for this portion of the research.

These procedures were approved by the Georgia Tech Institute Review Board (IRB# H19522). Consent and recording release form and Consent form were obtained from all subjects in Part 1 and 2. Forms can be seen in Appendix A.1.1 and Appendix A.1.2.

3.1 Portion 1: Survey

The purpose of the survey was to better understand people's perceptions and preferences for custom footwear. The literature indicates that the public has a growing expectation of customization of goods and services. This survey aims to bolster these findings with qualitative and quantitative responses. The survey was also used to identify potential subjects for part two and three of the study. By asking gender and shoe size, potential outlier female subjects were identified. The survey was distributed electronically and over social media channels. The only qualification for the survey was to be at least 18 years of age. After the subject agreed to qualifications of the survey, 9 questions were asked of the subjects in the survey. The full survey can be found in Appendix A.2.1.

3.1.1 Survey Results

A total of 68 subjects started the survey but not all participants completed every question. 63 subjects identified gender 38 female, 24 male, and 1 Non-Binary. The Results will focus on females who wear women's shoe sizes.

In Q3, "Have you ever purchased a pair of uncomfortable casual shoes, or work boot (shoes)?", 97.37% of females answered 'Yes', Table 5, where 83.33% of males answered 'Yes' Table 6. In the follow up question Q4, "What was uncomfortable about the casual shoes, athletic shoes, or work boots (shoes)?", 15 of the females specifically cited problems related to the width of the shoe. Shoe width was the most common complaint.

Table 5 – Portion 1 Survey, Q3 Female Responses

#	Answer	%	Count
1	Yes	97.37%	37
2	No	2.63%	1
3	I do not understand the question	0.00%	0
	Total	100%	38

Table 6 – Portion 1 Survey, Q3 Male Responses

#	Answer	%	Count
1	Yes	83.33%	20
2	No	16.67%	4
3	I do not understand the question	0.00%	0
	Total	100%	24

In Q5, "Would you purchase a pair of custom shoes? Personalized to fit your feet.", 91.89% of females answered 'Yes' , Table 7, where 87.50% of men answered 'Yes', Table 8. In the follow up question Q6, "Why would you purchase a pair of custom shoes?", 27 of the females specifically cited custom shoes would be comfortable or a better fit. 6 cited it could help with a physical ailment, i.e. back pain. 5 cited style or aesthetics.

Table 7 – Portion 1 Survey, Q5 Female Responses

#	Answer	%	Count
1	Yes	91.89%	34
2	No	8.11%	3
3	I do not understand the question	0.00%	0
	Total	100%	37

Table 8 – Portion 1 Survey, Q5 Male Responses

#	Answer	%	Count
1	Yes	87.50%	21
2	No	12.50%	3
3	I do not understand the question	0.00%	0
	Total	100%	24

As cited earlier in the paper, this thesis is focused on female outliers, <10 percentile and >90 percentile. In the questionnaire, 9 female subjects are suspected of falling into this range based on shoe size. Three subjects were <10 percentile and six subjects were >90 percentile. At least one from the bottom 10 percentile and one from the top 10 percentile are needed to participate in the upcoming research sections. In the next section these subjects were invited to participate in part 2 of the study.

3.2 Portion 2: Interview

Portion 2 involved in person interviews. The questions that were asked were both quantitative and qualitative. Subjects were asked 3 general question about shopping for shoes online. Then the subjects were asked to measure their left and right foot widths and lengths using 3 different measurement methods. The subjects then evaluated the measurement methods. The most important part of this portion of the research was collecting foot length and width measurements from the individuals. Two of the subjects were chosen based on foot length to move on to the third portion of the research. The interview questions can be found in Appendix A.2.2.

3.2.1 Subject Measurement Methods

Three measurement methods were selected for this portion of the study. Each method could be completed by the subject at home without assistance. The methods used different measurement instruments and technologies to document or simulate the measurements. The three methods were tape measure, Ritz Stick, and photo on paper, a smart phone was used to capture the image.

The tape measure method was inspired by methods suggested by various footwear manufactures. Nike supplies a 3 step approach for measuring foot size; stand with heel against a wall, measure heel to toe with a ruler or tape measure, and measure to the longest toe [24]. Foot length and width needed to be self-measured by the individual. To make the tape measure easier to use without assistance, the tape measure was glued to a piece of plywood with a rear fence to simulate a wall. A second tape measure was glued to a second piece of plywood with a peg to act as a stop for the side of the foot, Figure 4. This made measurements consistent across users.

Figure 4 – Tape Measure Method; Left for foot length, Right for foot width.

The Ritz Stick is a wooden caliper type device designed to measure foot length and width, Figure 5. The device can measure men’s, women’s, and children’s sizes all in one device. It was selected for its relative low cost compared to a bannock device and other caliper type measurement instruments.

Figure 5 – Ritz Stick

The photo on paper method was first discovered within the Doctor Scholl's Custom 3D printed Inserts iPhone application, Figure 6. A similar method is used on the Nike Fit application. This method simulates how computer vision technology can capture dimensions from a foot. This was a nonfunctioning method, no measurement data was collected from this method, but subjects answered questions about using the method.

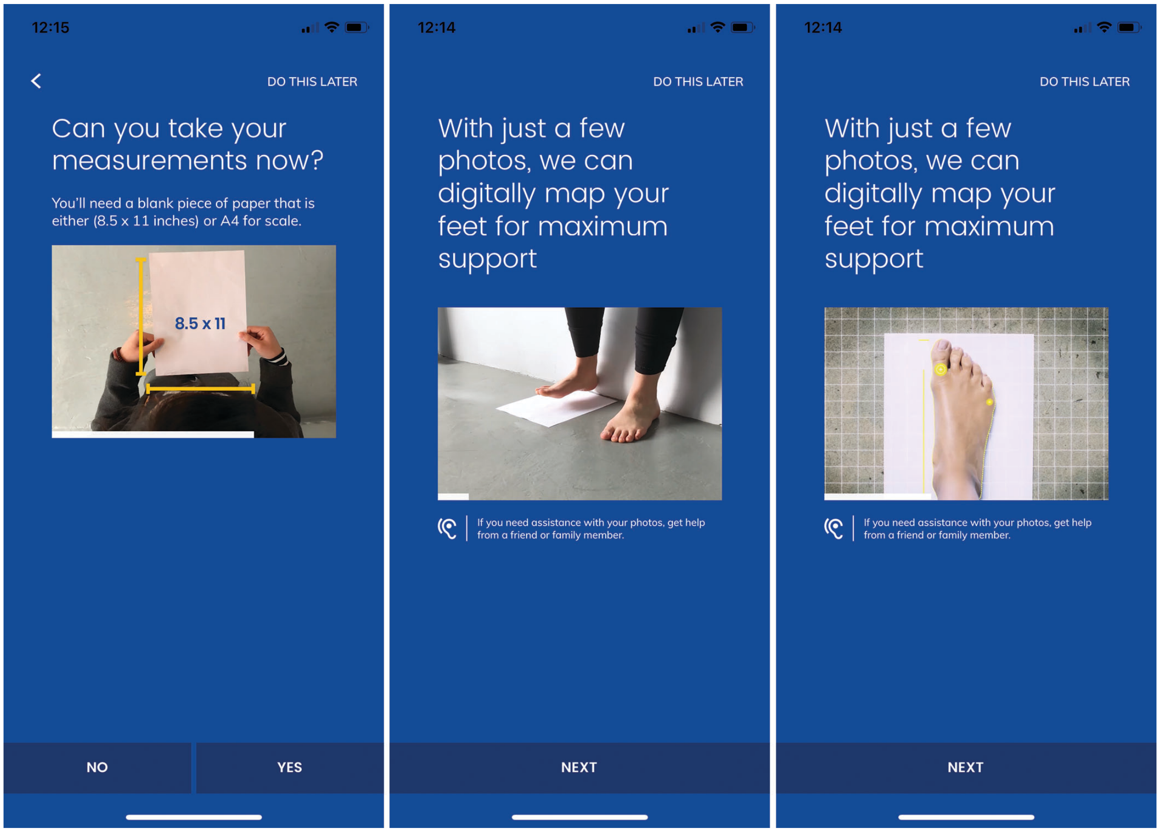

Figure 6 – Dr. Scholl's Custom 3D Printed Inserts Measurement Application [25].

Figure 7 – Photo On Paper

3.2.2 Interview Results

Seven subjects were interviewed in total, six were female and one was male. For the purposes of this thesis the results will focus on the female participants.

The first portion of the interview asked three semi-structured interview questions focused on shopping for and ordering shoes online. The first question that was asked was Q3, “Do you shop for shoes online? Why?” All the participants had shopped for shoes online but had different reasons for why they did. The second question Q4, “How do you determine your shoe size while shopping online?” Most participants relied on past experiences with the type of shoe and brand. The last intro question Q5, “How confident are you that a shoe will fit when you order it online?” The participants answers varied from “Quite confident” to “I make sure there is a good return policy.”

The subjects scored each measurement method after use on a scale from 0-10. Then the subjects ranked the three methods from their most favorite to least favorite.

Table 9 – Portion 2 Interview, Measurement Method Evaluation, Females

Questions	Tape Measure	Ritz Stick	Photo on Paper
How easy was this method of measuring your feet?	7.17	7.67	7.83
How confident are you that your measurement is accurate?	7.83	8.0	5.83
How likely are you to use a system like this at home?	4.33	5.8	9.83
Average Score	6.44	7.17	8.5

Table 10 – Portion 2 Interview, Measurement Method Ranking, Females

Instrument	1		2		3		Total
Tape Measure	0.00%	0	16.67%	1	83.33%	5	6
Ritz Stick	0.00%	0	83.33%	5	16.67%	1	6
Picture on Paper	100.00%	6	0.00%	0	0.00%	0	6

Of the seven subjects two were selected for the third portion of the research. The two selected subjects will be referred to as Subject 1 and Subject 2. Measurements from the tape measure method were averaged for each individuals foot and compared to CAESAR women's data for length and width.

Table 11 – Portion 2 Interview, Subjects 1 and 2 results averaged

SUBJECT	PERCENTILE GROUP	MEASURMENT	DIMENSION MM	PERCENTLE	Z SCORE
1	<10th	RIGHT FOOT LENGTH	222.67 mm	8.281th	-1.3864
		LEFT FOOT LENGTH	220.67 mm	6.1th	-1.5464
		RIGHT FOOT WIDTH	80 mm	2.4473th	-1.969
		LEFT FOOT WIDTH	80 mm	2.999th	-1.88
2	>90th	RIGHT FOOT LENGTH	265 mm	97.725th	2
		LEFT FOOT LENGTH	260.67 mm	95.09th	1.65
		RIGHT FOOT WIDTH	108.33 mm	97.807th	2.02
		LEFT FOOT WIDTH	109.67 mm	98.358th	2.13396

3.3 Prototype Design

To design a sandal outsole that can be quickly manipulated to accommodate various sizes requires the use of a parametric CAD program. Unlike other 3D CAD programs parametric CAD models can be quickly manipulated by changing dimensions. For this study a 3D CAD model was designed to accommodate two inputs, a person's foot length and foot width. These two measurements are the model's 'points of common uniqueness' that will differ from subject to subject and make the model custom to the individual. Length and width alone do not provide enough detailed information to create an accurate representation of the outline of a person's foot. With only two dimensions a rectangle would be formed. Other dimensions needed to be gathered from foot anthropometry and morphology studies to 'fill in the gaps'. Morphology in biology is, according to Encyclopedia Britannica, "the study of the size, shape, and structure of animals, plants, and microorganisms and of the relationships of their constituent parts" [9]. Understanding the proportional relationships between structures of the foot allows the driving parameters of length and width to control the size and shape of other portions of the foot.

3.3.1 Design Criteria

This project aims to design a parametric sandal outsole model for female size outliers, <10th percentile or >90th percentile, that can be manipulated based on foot dimensions and produced using additive manufacturing.

1. Design a sandal outsole in a parametric CAD software that can be easily manipulated with a subject's foot dimensions.
    a. The sandal will have straps to attach the outsole to the subjects foot
    b. Footwear much be designed with additive manufacturing constraints in mind.
    c. The sandal must produce an acceptable fit.

3.3.2 Prototyping tools and software

When designing this prototype, a software program that was capable of feature based parametric solid modeling was needed. Parametric Modeling is a process of modeling that relies on parameters, geometric dimensions and relations between dimensions [26]. Solidworks was used to model the outsole sandal prototype. This software was used because of its equations feature that allows for robust parametric modeling.

Cura was used to prepare the model for 3D printing. This software was also used to apply appropriate infill and layer thicknesses to the model.

The Ultimaker s5 3D printer was used to 3D print the outsole. This printer was used because of its print bed size, material selection, and accessibility.

3.3.3 Parametric CAD Model Design

Before the CAD work began a sketch was used to define the architecture of the sandal model. The initial sketch can be seen below in Figure 8.

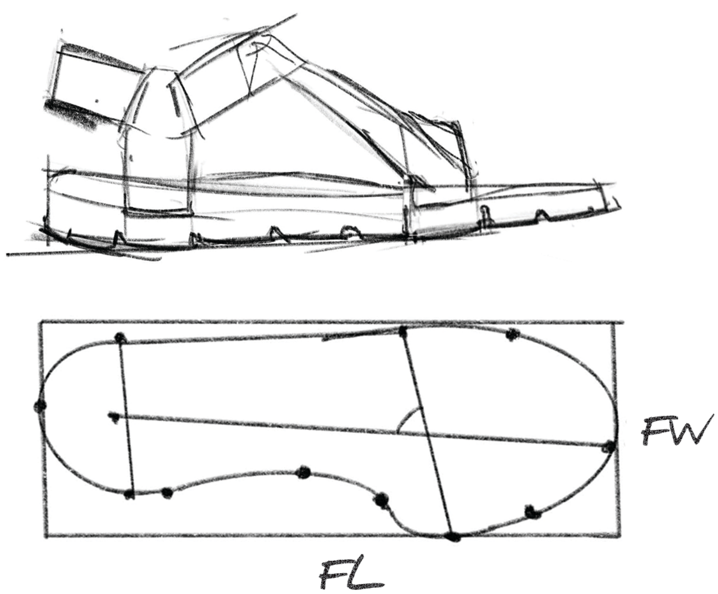

Figure 8 – Initial Sandal Outsole Sketch

3.3.3.1 Sole Outline

The first sketch of the Parametric CAD model contains the parameters that make up reference geometries that will drive the outline of the foot and therefore the outline of the sole. Before inputting the subjects' foot length and width values, tolerances were added to the measurements. 19 mm (10 mm+8 mm+1 mm) was added to the length and 9 mm (8 mm+1 mm) were added to the width. When fitting shoes between 9-12 mm of toe, clearance should be added to the longest toe [10]. For this model 10 mm was added to the length. An additional 8 mm was added to the length to account for the edge of the outsole that has a 4 mm fillet running around its perimeter plus 1 mm of tolerance. 8 mm was added to the width to account for the edge of the outsole that has a 4 mm fillet running around its perimeter plus 1 mm of tolerance. Figure 9 shows all the dimensions in sketch 1. In the first sketch, 8 parameters determined by the foot length FL, dimensions A-H, and 4 are determined by foot width, dimensions I-L. Figure 9 illustrates the dimensions and Table 12 describes how they were derived. The subjects' foot measurements were rounded to whole numbers before being inserted into the model.

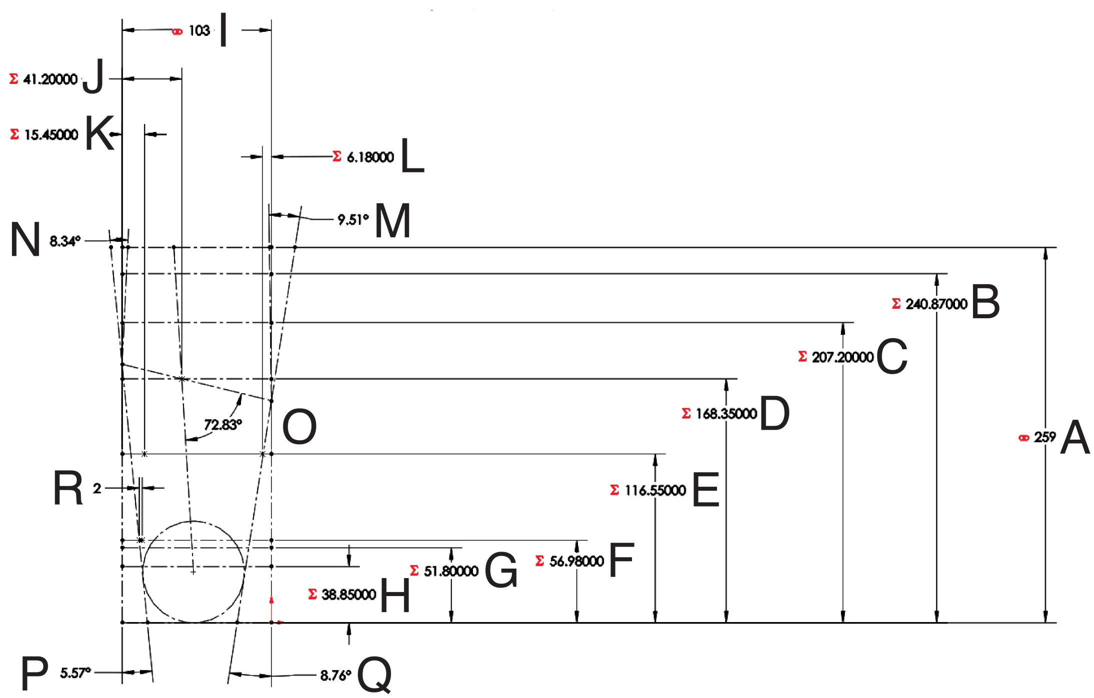

Figure 9 – Sketch 1 Dimensions

Table 12 – Parametric Rational for Sketch 1

#	VALUE	NAME	RATIONAL
A	FL * 1.00	FL=FOOT LENGTH+19	Foot length from subject measurement + 10 mm + 9 mm.
B	FL * .93	TOE 1 ANGLE ACCOMODATION	Outline curve anchor point
C	FL * .80	TOE 5 ANGLE ACCOMODATION	Outline curve anchor point
D	FL * .65	FOOT BREADTH LOCATION	The First Metatarsophalangeal Protrusion (MTP) is detected between 65% and 80% of foot length. The Fifth Metatarsophalangeal Protrusion (MTP) is detected between 50% and 80% of the foot length. 65% is the average of 50% and 80% [2, 4]. Paired with a constant Foot Breadth Angle of 72.82 these points stay within the prescribed range.
E	FL * .45	ARCH AESTHETIC	Outline curve anchor point
F	FL * .22	HEEL WIDTH LOCATION	Average female heel width location, according to Krauss 2008 article [11]
G	FL * .20	HEEL WIDTH REFERENCE	Reference Geometry
H	FL * .15	HEEL WIDTH REFERENCE	Reference Geometry
I	FW * 1.00	FW=FOOT WIDTH + 9	Foot width from subject measurement + 9 mm
J	FW * .40	MEDIAL BIAS	Used to subdivide the foot into halves 40% Medial 60% Literal [2]
K	FW * .15	AESTHETIC	Outline curve anchor point
L	FW * .06	AESTHETIC	Outline curve anchor point
M	9.51 DEGREES	TOE 5 ANGLE	Mean angle from Lee 2013 article [27]
N	8.34 DEGREES	TOE 1 ANGLE	Mean angle from Lee 2013 article [27]
O	72.82 DEGREES	FOOT BREADTH ANGLE	Mean angle from Lee 2013 article [27]
P	5.57 DEGREES	MEDIAL BALL LINE ANGLE	Mean angle from Lee 2013 article [27]
Q	8.76 DEGREES	LATERAL BALL LINE ANGLE	Mean angle from Lee 2013 article [27]
R	2 mm	SPACER	Prevents model from self-intersecting and causing failure.

Sketch 2 connects intersection points from Sketch 1 to form the outline of the sole. See Figure 10 for Sketch 2.

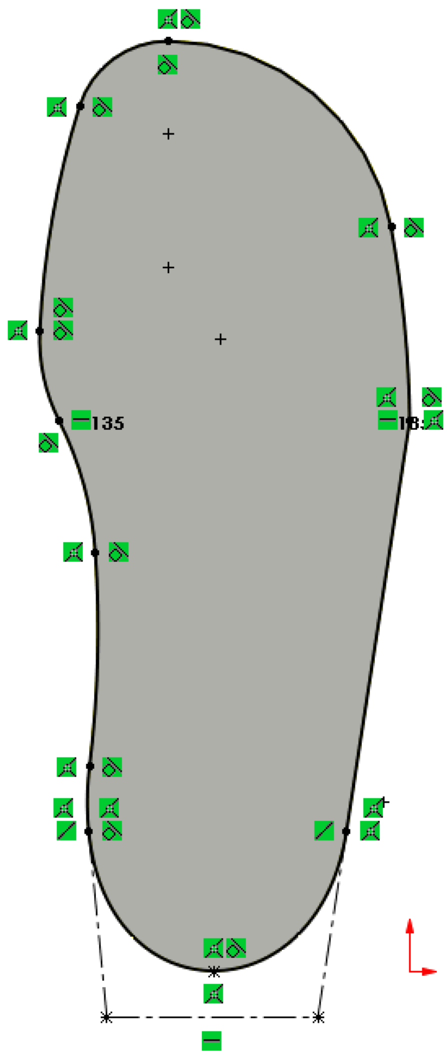

Figure 10 – Sketch 2, Curves intersect points from Sketch 1.

3.3.3.2 <u>Heel Drop</u>

The variable thickness of the sole or drop is constantly 25mm at the heel and 15mm at the toes Figure 11**.**

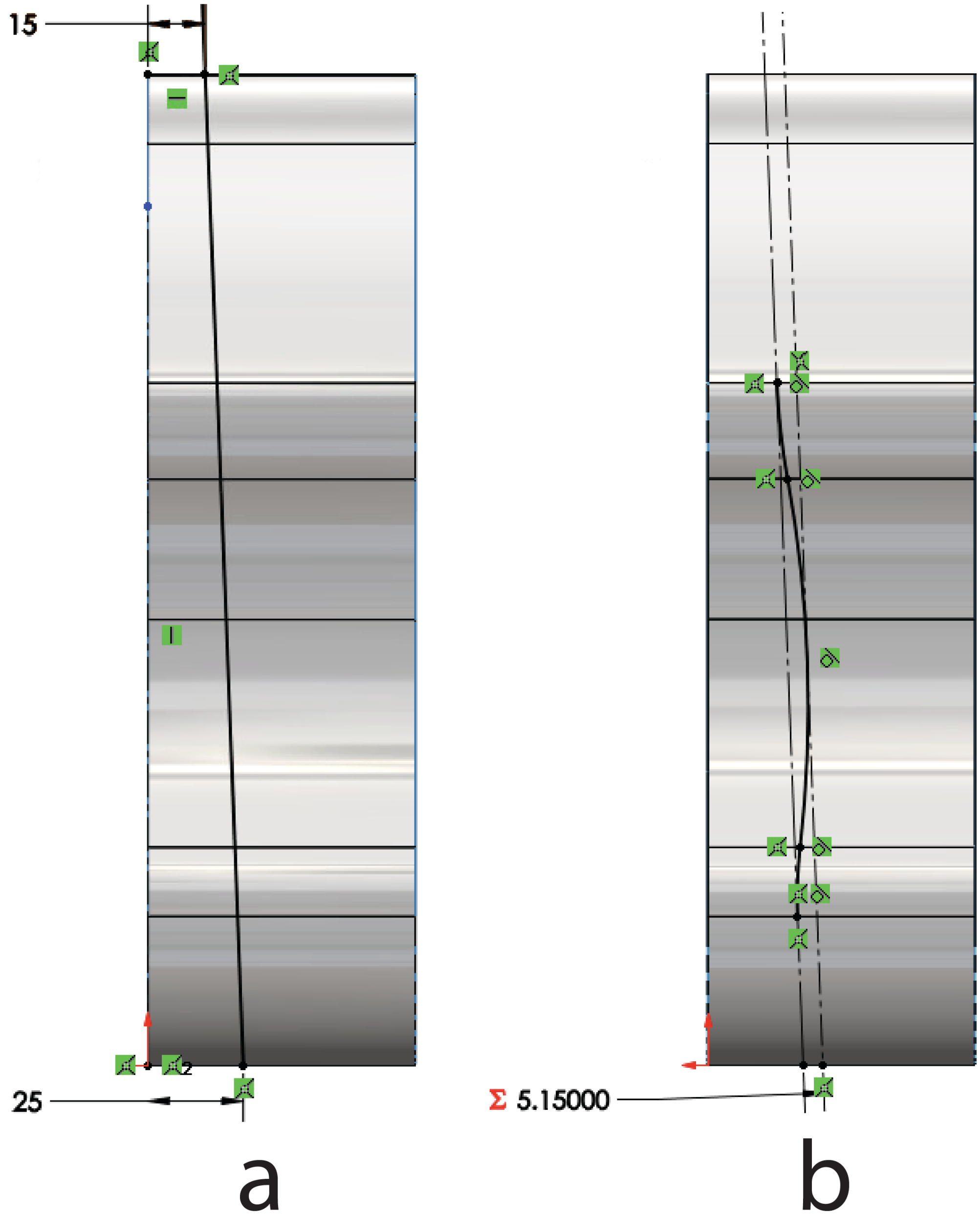

Figure 11 – Heel Drop (a) and Arch Design (b)

3.3.3.3 Arch Design

The arch on the insole of the part is designed to be a low arch and its height is equal to 5% of the FW, Figure 11.

3.3.3.4 Flex Zones

The flex zones straddle the foot breadth location and are parallel to the foot breadth angle. Flex area of a shoe is recommended to between 65% and 70% of the length of the shoe [11]. Scores designed into the sole for flex, Figure 12

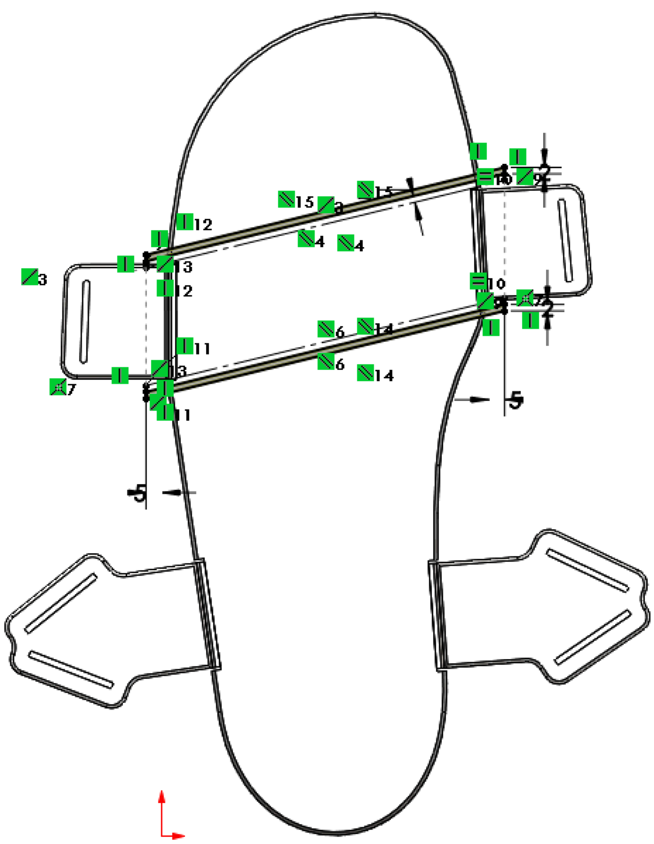

Figure 12 – Flex Zone & Strap Holders

3.3.3.5 Strap Holders

There were several iterations of the strap holders. The strap holders were placed near the Foot Breadth Location and Heel Width Location. The design used for the evaluation incorporated a living hinge so the strap holders could be printed flat, directly on the print bed, and folded and glued into place for final assembly. In Figure 12 the strap holders can be seen protruding from the sides of the model.

3.3.4 Design for Additive Manufacturing

The rest of the model's form is driven by constraints placed on it by additive manufacturing. This portion will be discussing Design for Additive Manufacturing DFAM. Most specifically designing the sole to be printed on the readily available Ultimaker S5 printer with TPU 95a material. The Ultimaker is an FDM 3D printer. TPU 95a is a semi-flexible thermoplastic polyurethane. Unlike other materials offered by Ultimaker TPU 95a is not supported to be used with any other materials. This means support material cannot be used in the design. Support material is useful in 3D printing so that voids and unsupported geometries can be constructed. It is generally recommended to maintain an angle of 45 degrees or greater from the build plate when designing parts without support.

3.3.4.1 Cushioning Infill

To make the outsole feel more like a shoe, proper cushioning was needed. In 3D printing a cushioned feel can be accomplished by using semi flexible material paired with an infill or lattice design. Using Cura's predefined infill of Box and Gyroid several test prints were made with varied degrees of infill as seen in Figure 13. In Cura, the amount of infill is determined by a percentage, 0% (no infill) - 100% (solid infill). The default infill setting is 10%.

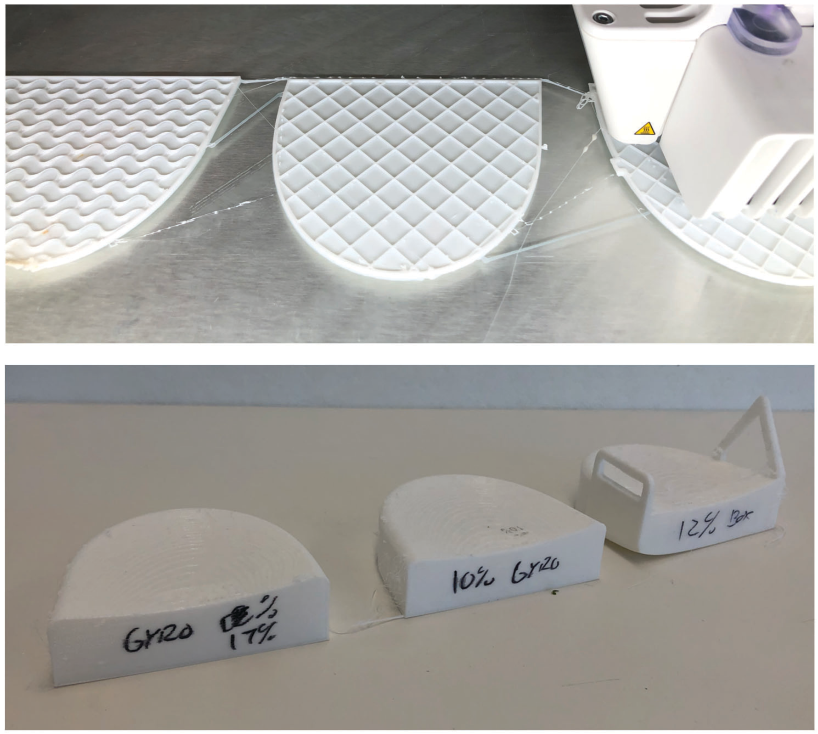

Figure 13 – Test infill; Top image shows gyroid (far left) and box (right) infills being printed. Bottom images shows resulting test pieces.

Gyroid is an interesting geometry and produced a robust yet cushioned feel with less material than the box infill. The samples were evaluated by hand without the use of any durometer tools. It was determined that a 16% gyroid infill gave the most foam like feel.

3.3.5 Fabricating

3.3.5.1 <u>3D Printing</u>

Test printing revealed some challenges with the original strap placements. The first iteration of strap holder was a triangular design. The unsupported structures failed during test printing Figure 14. A redesign of strap holders with a living hinge were designed so they could be printed flat then folded up and glued into place Figure 15.

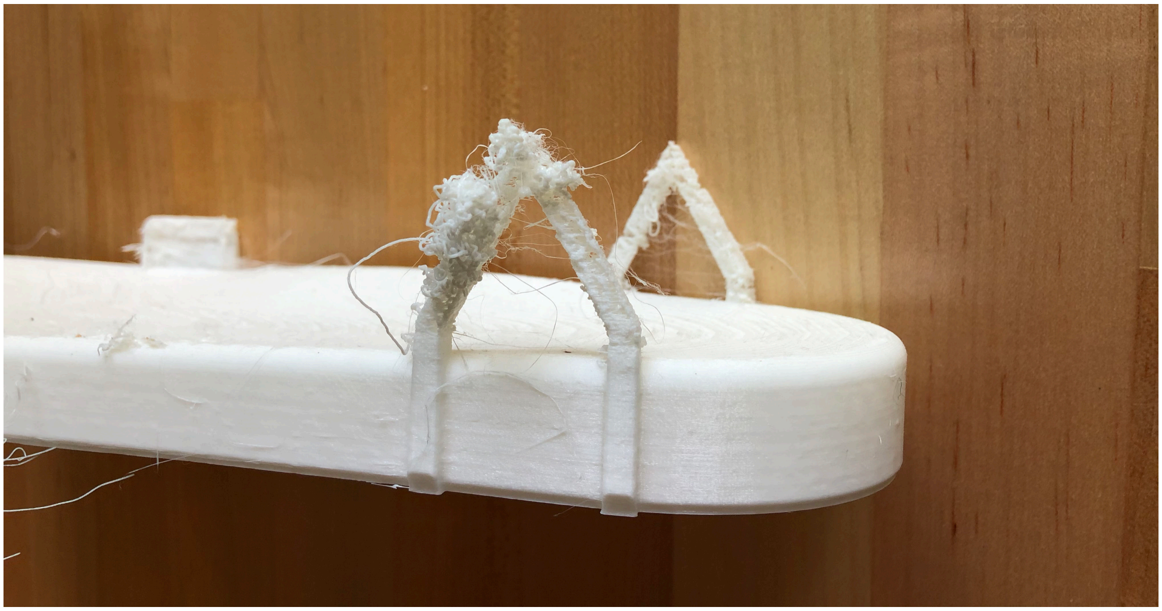

Figure 14 – Failed strap holder design

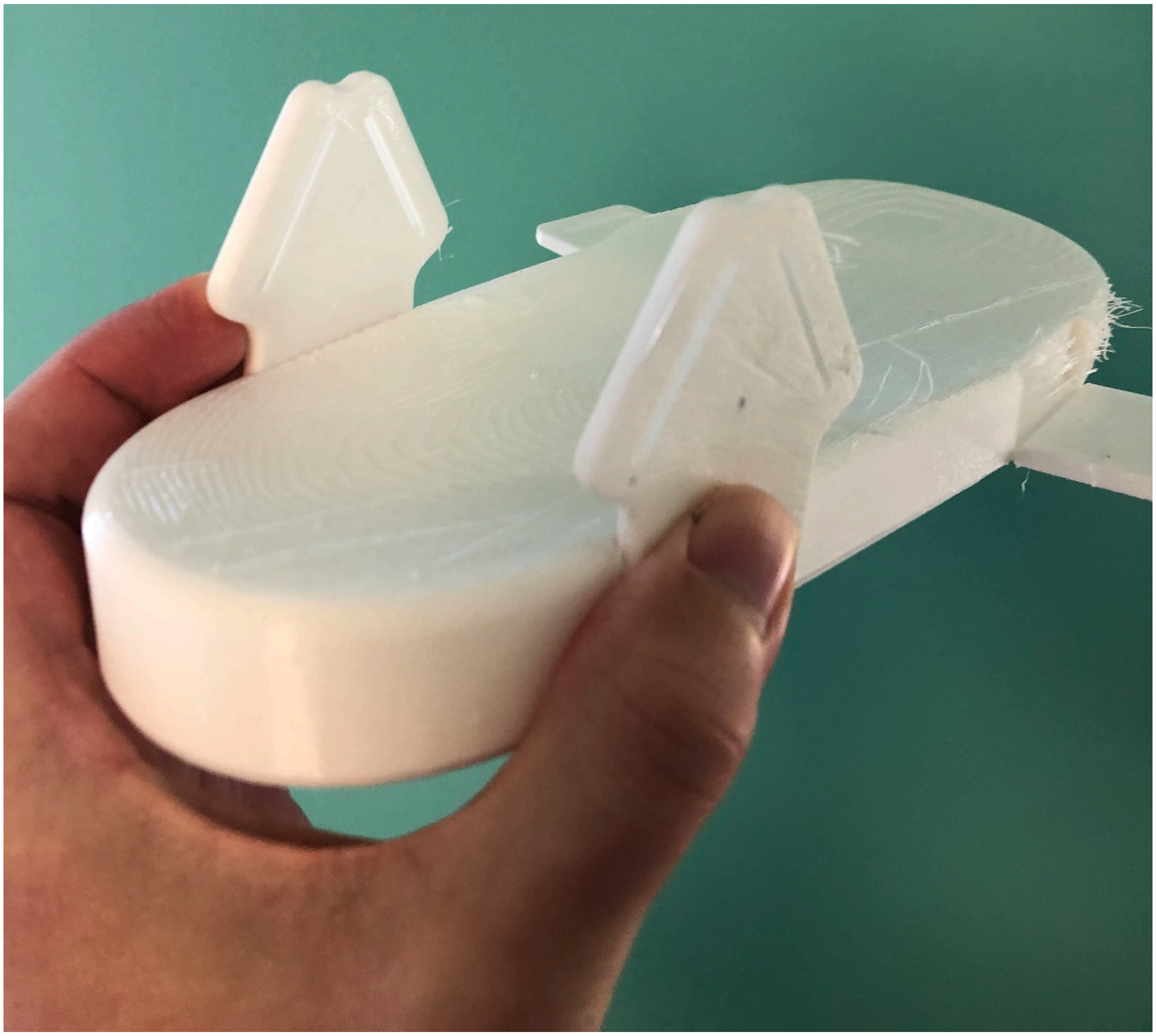

Figure 15 – Strap holder; living hinge design

Once the strap holders were redesigned final models were printed for the subjects, Figure 16.

Figure 16 – Final Prototypes Before Assembly

3.3.5.2 Assembly

Adjustable straps were sewn onto the sandal outsoles so the subjects could attach the outsoles to their feet. The strap holders were then folded and glued into place.

3.3.6 Resulting Prototypes

The resulting prototypes. A left and right sandal model was prototyped for the subjects, Figure 17.

Figure 17 – Final Prototypes

3.4 Portion 3: Evaluation

Due to Covid-19, this portion of the research had to be conducted over Bluejeans video interview. Subject 1, <10 percentile, and Subject 2 ,>90 percentile, were the subjects of the interview and prototype evaluation. A semi-structured interview was conducted after the subjects unboxed the prototyped sandals. The subjects tried on the sandals and gave initial feedback on the fit. Using a 0-10 Likert scale the subject were asked to rate overall fit, length fit, and width fit. The subjects were then asked to photograph the sandals on their feet from multiple angles and send the images to the interviewer. Interview questions can be found in the Appendix A.2.3.

3.4.1 Evaluation Results

Subject 1, <10 percentile, for question 4 the subject rated the overall fit as 9/10. On question 5 the subject rated the length as 10/10. On question 6 subject rated the width at 9/10. For question 7, “Is this an acceptable fit to you?”, the subject answered “Yes.”

Subject 2, >90 percentile, for question 4 the subject rated the overall fit as 9/10 but specified that the left fit was 10/10. On question 5 the subject rated the length as 9/10 but specified left length was 10/10. On question 6 subject rated the width at 10/10. For question 7, “Is this an acceptable fit to you?”, the subject answered “Yes.”

3.4.2 Photography

3.4.2.1 <u>Subject 1</u>

Photos order in Figure 18 starting from top left and moving to the right. Top view of left foot, Top view of right foot, medial view of left foot, medial view of right foot, lateral view of left foot, and lateral view of right foot.

Figure 18 – Subject 1 test fit photos; Top, Medial, and Lateral

3.4.2.2 <u>Subject 2</u>

Photos order in Figure 19 starting from top left and moving to the right. Top view of left foot, Top view of right foot, medial view of right foot, lateral view of left foot, and lateral view of right foot.

Figure 19 – Subject 2 test fit photos; Top, Medial, and Lateral.

CHAPTER 4. DISCUSSION

This thesis sought to produce a sandal outsole designed with mass customization methods, parametric modeling and 3D printing, for so called female size outliers, females in the <10% or >90% in foot length based on data collected by CAESAR (Civilian American and European Surface Anthropometry Resource) [7]. This selected group of individuals was chosen because women in this group often lack options for properly fitting footwear as illustrated in Table 1. The major findings of this thesis confirm that females that have had issues finding acceptable fitting footwear are open to purchasing custom footwear, are open to measuring their own feet at home and find the prototyped sandal designed for mass customization an acceptable fit.

Figure 20 illustrates the configuration architecture of the mass customization process used in this thesis. The user model represents foot length and width from the user. The configuration knowledge base contains the parameters that make up the CAD model. The origins of these parameters can be reviewed in Table 12. The configuration system in this case is the Solidworks CAD model. The users' dimensions are input into the CAD model and are connected to the parameters within the model. The output is configuration, the sandal sole CAD model that is then 3D printed to meet the users' inputs [23].

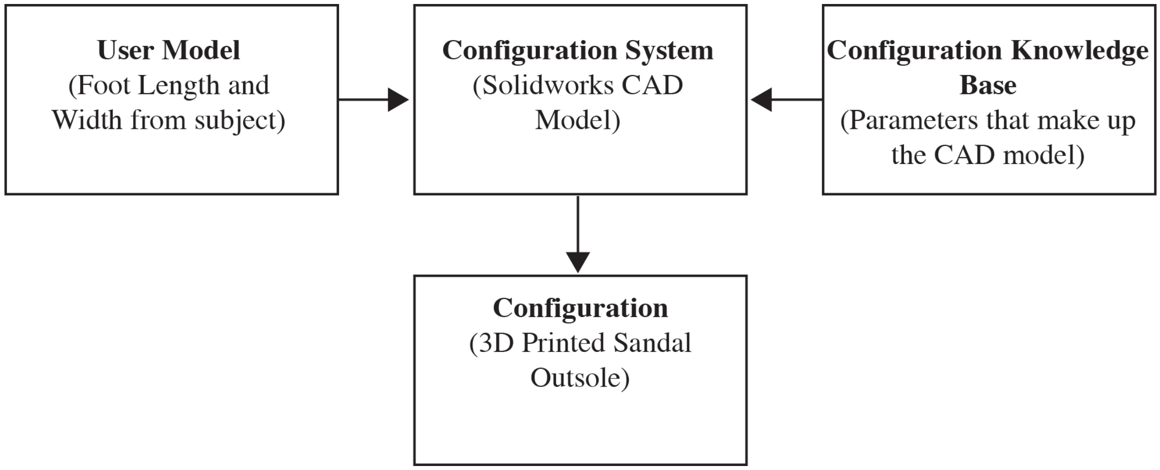

Figure 20 – Sandal Outsole Configuration Architecture [23]

The research also proves that a sandal model can be designed to accept 2-foot measurement parameters and be 3D printed to produce an acceptable fit. This process that utilizes 3D printing reduces the steps needed to produce a piece of footwear. In comparison to the traditional manufacturing flow of footwear, Figure 2, the sandal manufacturing flow uses 2 fewer steps in the process, Figure 21. These are important findings because they can further advance efforts of mass customization in the footwear industry.

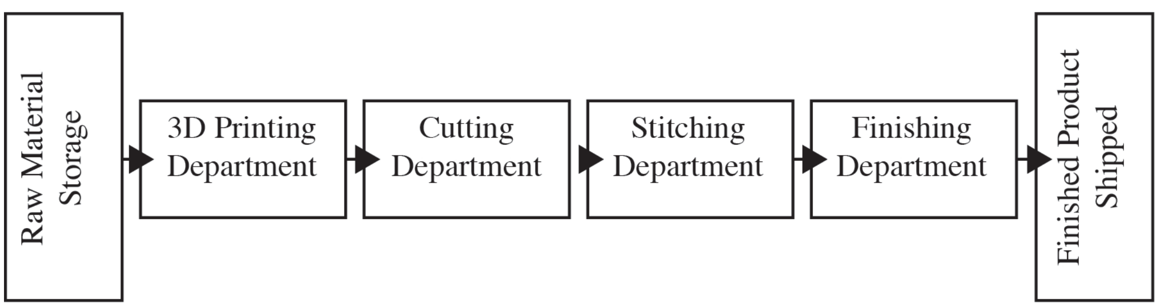

Figure 21 – Sandal Manufacturing Flow

Female shoe sizing has long been a derivative of male footwear sizes. Shoes sized differently across manufactures Table 2, inaccurate last grading methods and shoes being categorized by a single dimension have all added to the struggles of finding acceptable fitting shoes for female outliers.

4.1 Evaluating the Results

4.1.1 Portion 1 Evaluation

The first portion of the research sought to understand the nuances and most common issues with poor fitting footwear. Nearly all the females surveyed said they had purchased uncomfortable shoes before and the most common complaints were issues dealing with the width of the footwear. Looking specifically at the qualitative answers of the 9 females who are considered outliers, because they have a shoe size 5.5 or small or 9.5 or larger, some interesting and unexpected details emerge. All 9 females said they had purchased uncomfortable footwear before but only 7/9 said they would purchase custom footwear made to fit their feet. The 2 that would not purchase custom footwear cited expense as being a reason why they would not. Currently custom shoes are expensive but as new manufacturing techniques emerge and become more established prices will drop. The material cost of the prototypes were between 13 and 20 dollars per single sandal, Table 13, but labor and time on the 3D printing machine would greatly increase the costs. One participant wrote, “I guess I expect them to be really expensive. My shoes don't tend to last very long so I usually don't buy super expensive shoes.” The second participant wrote, “They would likely be very expensive and I can usually find other shoes that fit just fine.” The second quote was from a woman who was right at the 90th percentile with a shoe size of 9.5. The largest female size recorded was a size 12. She had this to say about why she would purchase a custom pair of shoes. “I have a hard time finding shoes anyways because I’m at the upper end of women’s shoe sizes, and those shoes that do exist in my size tend to be uncomfortable (but I'll have to deal with it because I don't have another choice), or they'll be spectacularly ugly."

Table 13 – Cost of prototype materials. All costs in USD.

Subject	Foot	TPU Grams	TPU Cost	Nylon Strap inches	Nylon Strap Cost	Hook& Loop inches	Hook& Loop Cost	Hardware #	Hardware Cost	Total Cost
1	Right	106	9.858	31.89	0.54213	5.9	1.947	1	1.58	$13.93
1	Left	105	9.765	31.89	0.54213	5.9	1.947	1	1.58	$13.83
2	Right	155	14.415	38.5	0.6545	7	2.31	1	1.58	$18.96
2	Left	156	14.508	38.5	0.6545	7	2.31	1	1.58	$19.05

As was expected as sizes go up choices drop off and negatively affect the customers. Two of these 9 outlier subjects agreed to participate in the last 2 parts of the study and ultimately test fitted the prototype.

4.1.2 Portion 2 Evaluation

In portion 2 of the study, the subjects measured their own feet with three devices. Tape measure, Ritz stick, and photo on paper. The subjects were asked to measure each foot three times with the tape measure and Ritz stick. The subject took one photo of each foot on the paper. The photo was a simulation of computer vision and did not record any measurements. The measurements recorded from the tape measure were used in the prototype for the subjects that participated in part 3. The photo on paper was the most popular form of measurement followed by the Ritz stick. The photo on paper was also the method the subjects would most likely use at home. It seemed to produce an enjoyable experience and explains why this method has been used by companies like Nike and Dr. Scholl's in their applications [25]. In this study, the two suspected outlier subject's foot length measurements were confirmed as outliers. The individuals' foot widths were even greater outliers than the individual's lengths, Table 11.

4.1.3 Portion 3 Evaluation

In portion 3, Subject 1, <10th percentile, and Subject 2, >90th percentile, tried on the 3D printed prototype sandals. Subject 1 gave the overall fit a 9/10 and the width as a 9/10. Her main complaint was the width at the heel. Particularly, the strap holder in that area was pushing up against her heel. She also cited the strap across the toes as being a little far back. Despite these comments, she felt it was an acceptable fit. Subject 2 rated the left sandal as 10/10 overall in length, and width. She called out the right sandal as 9/10 overall 9/10 for length and 10/10 for width. She said the right one looked bigger than the left. Despite this, she said it was acceptable fit. When asked if she had anything else to share, she mentioned the strap holder was a little tight against her foot.

To further understand the rankings, the photography the subjects provided was examined and revealed that foot orientation on the sandal could be why the sandals did not receive full marks. Foot orientation can be manipulated by adjusting the straps on the sandal and shifting the foot into a more ideal position.

At this point, the question must be asked, "How imperfect can an acceptable fit be in mass customization?" Current footwear solutions provide a mass customization solution by finding a best fit or "good enough" fit through measuring a foot then matching it to a relevant last [11]. However, the solutions on the market are yet to offer a specific customizable solution for people who have outlier foot sizes. These solutions still required molds and lasts.

4.1.4 Parametric CAD Model Design and Prototype Fabrication

As confirmed in Portion 3 of the research the Solidworks parametric CAD model functioned as expected and produced an acceptable fit for the subjects in this study. However, both subjects mentioned the strap holders as pushing against their foot in an undesirable way. Subject 1 cited the strap holder in the heel area of her foot and Subject 2 cited the strap holder at the foot breadth location. Fit tests with more subject could potential revile more flaws to the design.

The fabrication of the prototypes on the 3D printer revealed a flaw to the first strap holder design. The strap holder was redesigned so they could be printed more reliably. The average print time of the sandal outsoles for subjects 1 and 2 was 15 hours and 46 minutes. As 3D printers evolve it can be expected that print times will decrease in the future.

4.2 Limitations of the Study

This thesis was partially conducted during the Covid-19 pandemic of 2020. Due to the burden of the pandemic, several accommodations and modification had to be made to the study. In person interviews were cancelled or rescheduled to online video conferences due to the health risk that they posed. This made evaluating the fit of the sandals on the subjects difficult. To compensate, the subjects were asked to photograph the prototype on their foot.

Another limitation of this study is the number of individuals that participated who were outliers. In the first portion of the study, 9 out of the 36 women were outliers. The second portion and third portion only had 2 identified. Prototyping, costs, and time played a factor in limiting the size of subjects. With more funding and time, it could have been feasible to recruit more female outlier subjects.

In the design of the sandal, most of the design time went into defining the sole outline with 2 parameters. Straps were made adjustable so they could be tightened to fit. A higher number of parameters would have improved fit but would have required greater processing time and technology that was not explored in this study.

It could be argued that this study was too broad in its definition of outliers. The 10th percentile was selected because of the drop off in shoe offerings at that size. This percentile mirrors to the 90th percentile on the other side of the bell curve. There was a drop off at this size but there were more sizes available to this group than to the <10th percentile.

The 3D printing technology used in this study limited certain aspects of the design of the sandal. For instants, the strap holders had to be redesigned to print flat and fold up into place. The size of the printer also had limitations on the maximum size of the sandal and limited the number of sandals that could be printed at a time. If another printer would have been used different DFAM criteria would've been used in the design of the outsole.

4.3 Future Research

There are plenty of directions that this research could go in the future. This study limited the research to the outsole of a sandal defined by length and width measurements. The next iteration could explore adding parameters to the model. Parameters that could be added to the model include arch height and heel width.

A researcher could explore full 3D printed solutions that includes an upper. Investigating an upper would require greater research into foot morphology in order to define parameters needed to execute such a design. Manufacturing techniques that do not require a last would also need to be investigated in a shoe design that includes an upper.

Future studies could also incorporate styling elements and color options. This solution would require the development of a configurator or interface for the subjects to select their modifiers.

CHAPTER 5. CONCLUSION

In conclusion, this thesis explored one avenue of how the ideas of mass customization can be applied to a sandal for female outliers. Though mass customization has been adopted in various forms already, this thesis proposes a made to measure approach for 3D printed sandals specifically for female outliers. The process and results of this thesis should encourage the footwear industry to pursue made to measure 3D printed footwear for outlier groups who fall outside of traditional sizing systems. With improving technologies sizing systems as we know them may become a relic of the past.

APPENDIX A. RESEARCH DOCUMENTS

A.1 Consent Forms

A.1.1 Consent & Recording Release Form

Consent & Recording Release Form - Adult

I agree to participate in the study conducted and recorded by the Georgia Institute of Technology and Robert Patterson.

I understand and consent to the use and release of the recording by the Georgia Institute of Technology and Robert Patterson. I understand that the information and recording is for research purposes only and that my name and image will not be used for any other purpose. I relinquish any rights to the recording and understand the recording may be copied and used by the Georgia Institute of Technology and Robert Patterson without further permission.

I understand that participation in this usability study is voluntary and I agree to immediately raise any concerns or areas of discomfort during the session with the study administrator.

Please sign below to indicate that you have read and you understand the information on this form and that any questions you might have about the session have been answered.

Date:**_________**

Please print your name: ____

Please sign your name: ____

Thank you!

We appreciate your participation.

U.S. Department of Health & Human Services - 200 Independence Avenue, S.W. - Washington, D.C. 20201 1

A.1.2 Consent Form

Consent Form (Adult)

I agree to participate in the study conducted by the Georgia Institute of Technology and Robert Patterson.

I understand that participation in this usability study is voluntary and I agree to immediately raise any concerns or areas of discomfort during the session with the study administrator.

Please sign below to indicate that you have read and you understand the information on this form and that any questions you might have about the session have been answered.

Date: _________

Please print your name: ____

Please sign your name: ____

Thank you!

We appreciate your participation.

U.S. Department of Health & Human Services - 200 Independence Avenue, S.W. - Washington, D.C. 20201 1

A.2 Survey and Interviews

A.2.1 Portion 1 Survey

Custom Footwear

Start of Block: Default Question Block

Q1 The purpose of this research project is to understand people’s perceptions and preferences for custom footwear. This is a research project being conducted by Robert Patterson at Georgia Institute of Technology.

Your participation in this research study is voluntary. You may choose not to participate. If you decide to participate in this research survey, you may withdraw at any time. If you decide not to participate in this study or if you withdraw from participating at any time, you will not be penalized.

The procedure involves filling an online survey that will take approximately 5 minutes. Your responses are subject to publication but will be made anonymous. The survey questions will be about your preference towards custom footwear.

We will do our best to keep your information confidential. All data is stored in a password protected electronic format. The results of this study will be used for scholarly purposes only and may be shared with Georgia Institute of Technology representatives.

If you have any questions about the research study, please contact Robert Patterson at robertpatterson@gatech.edu. This research has been reviewed according to Georgia Tech’s IRB procedures for research involving human subjects.

Top of Form

ELECTRONIC CONSENT: Please select your choice below.

Clicking on the "agree" button below indicates that:

• you have ready the above information
• you voluntarily agree to participate
• you are at least 18 years of age

If you do not wish to participate in the research study, please decline participation by clicking on the "disagree" button.

Bottom of Form

○ Agree (1)

○ Disagree (2)

Q1 What is your name? Please provide your first name only.

____

Q2 What is your gender?

- ○ Male (1)
- ○ Female (2)
- ○ Other (specify) (3) ____

Q3 Have you ever purchased a pair of uncomfortable casual shoes, athletic shoes, or work boot (shoes)?

- ○ Yes (1)
- ○ No (2)
- ○ I do not understand the question (3)

Q4 What was uncomfortable about the casual shoes, athletic shoes, or work boots (shoes)? Please describe what about the shoes made them uncomfortable.

Q5 Would you purchase a pair of custom shoes? Personalized to fit your feet.

- ○ Yes (1)
- ○ No (2)
- ○ I do not understand the question (3)

Q6 Why would you purchase a pair of custom shoes?

Q7 Why would you not purchase a pair of custom shoes?

Q8 What size shoe do you usually wear?
Men's or Women's (1)
Size (2)
Width (3)
Empty

Q9 Please provide an email so that we can reach out to you about future research.

End of Block: Default Question Block

Page 3 of 3

A.2.2 Portion 2 Interview

Custom Footwear (Portion 2)

Start of Block: Default Question Block

(Interviewer)
Intro,
Portion 2
The purpose of this research project is to understand people's perceptions and preferences for footwear. This is a research project being conducted by Robert Patterson at Georgia Institute of Technology.
Your participation in this research study is voluntary. You may choose not to participate. If you decide to not participate in this research, you may withdraw at any time. If you decide not to participate in this study or if you withdraw from participating at any time, you will not be penalized.
The procedure involves an interview portion as well as a foot measurement activity that will take approximately 20 minutes. Your responses are subject to publication but will be made anonymous. The interview questions will be about your preference towards footwear.
We will do our best to keep your information confidential. All data is stored in a password protected electronic format. The results of this study will be used for scholarly purposes only and may be shared with Georgia Institute of Technology representatives.
If you have any questions about the research study, please contact Robert Patterson at robertpatterson@gatech.edu. This research has been reviewed according to Georgia Tech's IRB procedures for research involving human subjects.

Please sign the following consent forms, Consent Form and Recording Consent From.

Q1 What is your name? Please provide your first name only.

____

Q2 What is your gender?

○ Male (1)

○ Female (2)

○ Other (specify) (3) ____

Q3 Do you shop for shoes online? Why?

____

Q4 How do you determine your shoe size while shopping online?

____

Q5 How confident are you that a shoe will fit when you order it online?

____

(Interviewer) Introduce Measurement Methods:

Tape Measure, Use the tape measure to measure your foots length and width (repeat for other foot)

Ritz Stick, Use the Ritz Stick to Measure your foots length and width (repeat for other foot)

Picture On Paper. Please take a photo of your foot on top of a piece of paper with heel against the wall (repeat for other foot)

Using the 3 different types of measurement devises measure your foot according to the directions and record your measurements where noted. If you have any questions at any time, please ask.

Photo instructions and description of each measurement type will be supplier.

Questions 6-8 will be repeated for each measurement type.

Q6 On a scale of 0-10. How easy was this method of measuring your feet?

- 0 (0)
- 1 (1)
- 2 (2)
- 3 (3)
- 4 (4)
- 5 (5)
- 6 (6)
- 7 (7)
- 8 (8)
- 9 (9)
- 10 (10)

Q7 On a scale from 0-10, How confident are you that your measurement is accurate?

- ○ 0 (0)
- ○ 1 (1)
- ○ 2 (2)
- ○ 3 (3)
- ○ 4 (4)
- ○ 5 (5)
- ○ 6 (6)
- ○ 7 (7)
- ○ 8 (8)
- ○ 9 (9)
- ○ 10 (10)

Q8 On a scale from 0-10, How likely are you to use a system like this at home?

○ 0 (0)

○ 1 (1)

○ 2 (2)

○ 3 (3)

○ 4 (4)

○ 5 (5)

○ 6 (6)

○ 7 (7)

○ 8 (8)

○ 9 (9)

○ 10 (10)

Q9 Rank the different measurement methods from your most favorite to least favorite.
______ Tape Measure (1)
______ Ritz Stick (2)
______ Picture on Paper (3)

Q10 Is there anything else you want to share?

____

End of Block: Default Question Block

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A.2.3 Portion 3 Interview

Custom Footwear (Portion 3)

Start of Block: Default Question Block

(Interviewer)
Intro,
Portion 3
The purpose of this research project is to understand people's perceptions and preferences for footwear. This is a research project being conducted by Robert Patterson at Georgia Institute of Technology.
Your participation in this research study is voluntary. You may choose not to participate. If you decide to not participate in this research, you may withdraw at any time. If you decide not to participate in this study or if you withdraw from participating at any time, you will not be penalized.
The procedure involves an interview portion as well as a foot measurement activity that will take approximately 20 minutes. Your responses are subject to publication but will be made anonymous. The interview questions will be about your preference towards footwear.
We will do our best to keep your information confidential. All data is stored in a password protected electronic format. The results of this study will be used for scholarly purposes only and may be shared with Georgia Institute of Technology representatives.
If you have any questions about the research study, please contact Robert Patterson at robertpatterson@gatech.edu. This research has been reviewed according to Georgia Tech's IRB procedures for research involving human subjects.

Please sign the following consent forms, Consent Form and Recording Consent From.

Q1 What is your name? Please provide your first name only.

____

Q2 What is your gender?

○ Male (1)

○ Female (2)

○ Other (specify) (3) ____

(Interviewer) In the previous study you recall you measured your foot using various methods.

This is the output of that measurement. (reveal to the participant the 3D printed prototype Sandal that fits their measurements.)

Q3 What are your first reactions to this piece of footwear?

____

(Interviewer) Please put it on your foot and stand up. *Participant should be wearing thin socks. If not, brand new socks will be provided.*

Q4 On a scale from 0-10, How well does this piece of footwear fit your foot?

- ○ 0 (0)
- ○ 1 (1)
- ○ 2 (2)
- ○ 3 (3)
- ○ 4 (4)
- ○ 5 (5)
- ○ 6 (6)
- ○ 7 (7)
- ○ 8 (8)
- ○ 9 (9)
- ○ 10 (10)

Q5 On a scale from 0-10, How well does this piece of footwear fit your foot’s length?

- 0 (0)
- 1 (1)
- 2 (2)
- 3 (3)
- 4 (4)
- 5 (5)
- 6 (6)
- 7 (7)
- 8 (8)
- 9 (9)
- 10 (10)

Q6 On a scale from 0-10, How well does this piece of footwear fit your foot's width?

○ 0 (0)

○ 1 (1)

○ 2 (2)

○ 3 (3)

○ 4 (4)

○ 5 (5)

○ 6 (6)

○ 7 (7)

○ 8 (8)

○ 9 (9)

○ 10 (10)

Q7 Is this an acceptable fit to you?

Q8 Is there anything else you want to share?

End of Block: Default Question Block

(Interviewer) Please stand with your feet at shoulder length apart while I photography your foot to document fit. *Subjects photographed there own feet.

Photograph, Anterior (Front), Posterior (Back), Medial (Inside), Lateral (Outside), Dorsal (Top)

If the foot is hanging over the foot bed this indicates a poor fit.

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